A COMPACT, HIGH-PERFORMANCE HDTV CAMERA WITH FOUR-CCD CHIPS

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Abstract-A compact, high-performance and yet less-expensive camera is urgently needed to create more diverse and flexible HDTV program productions. In order to meet the demand, we propose a completely new image acquisition system with four CCDs, two CCDs for green light, one for red, and the other for blue.

The major purpose of our system is to obtain high-quality pictures with less pixel-number CCDs. The reduction in the number of pixels results in wider dynamic range, higher aperture ratio and low cost. The resolution power is secured by adding one more CCD to the conventional three-CCD system.

We succeeded in improving the resolution by introducing spatial pixel offset imaging, in which the two G-CCDs are aligned by one-half pitch of a pixel and one of them is aligned with the R-CCD and the other with the B-CCD. This new method has two major advantages: it prevents resolution degradation caused by chromatic aberration and improves the resolution of colored signals over a wide range.

The prototype camera has fully satisfied HDTV quality requirements : limiting resolution 1200 TV lines, sensitivity F5 at 2000lux, dynamic range 500%, SNR 52dB.

I. INTRODUCTION

More than two years have passed since regular High-definition television (HDTV) broadcasting started in Japan. With more low-priced receivers becoming available, the project is now entering a stage of expansion. The production of HDTV programs also needs to get more sophisticated. To meet the demand, we have been trying to supply a low-cost HDTV camera which is small, light and easy to carry.[1]

The trend in HDTV cameras is away from the long-used pickup tubes to CCDs. CCD imagers need to have approximately two million pixels to satisfy the HDTV standard.[2] But a large number of pixels necessarily reduces the area of pixels, which gives rise to a number of problems including a narrower dynamic range, a drop in the aperture ratio, degraded highlight characteristics and lower yield. Because of this, many of today's CCD cameras with two million pixels adopt the 1-inch optical system[3][4], forcing to use large and heavy lenses and fail to meet the demand for more compact program production.

To solve this problem, the new method we are proposing here for the 2/3-inch CCD camera, that is smaller optical format, has 1.3 million pixels. With this smaller pixel number than two million, we intend to prevent the pixel area from becoming too small, secure the necessary CCD performance and make up for the lack of resolution of each single imager by the special image-pickup system. In this new system, a camera is equipped with four CCDs whereas almost all TV cameras for broadcasting have three imagers, termed the RGB system. Two of the four CCDs are assigned for the green (G) light component and one each for red (R) and blue (B) in our system. This method puts more emphasis on the resolution of the green signal than on that of the red and blue signal. Therefore it is very efficient and compatible with human visual characteristics because they are characterized by a greater sensitivity to luminance signals than to chromatic signals and more than 70% of HDTV luminance signals come from the green component.

This paper describes the concepts and features of the new four-CCD imaging system.

II. FOUR-CCD IMAGING SYSTEM

Fig. 1 shows the comparison of the conventional RGB prism and the new four-CCD prism. Color separation prism for the four-CCD imaging system is essentially a conventional RGB prism with the addition of a half mirror in order to separate the green light into two portions. Of the incident beams, blue is reflected by the first dichroic surface, and then red by the second surface. Blue and red are each reflected once more before they are led to their own CCDs. The remaining green is then halved by the half mirror; the one moving straight ahead reaches the G1 CCD, while the other half is reflected again before arriving at the G2 CCD. This prism is designed in compliance with the 2/3-inch optical system standards for broadcasting camera.

The application of spatial-pixel-offset imaging to the four-CCD

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system was one of our major concerns. Conventionally, to enhance the resolution power in multi-CCD systems, the spatially offset imaging method has been employed This method aims to suppress alias signals and increase the volume of transmitted information by staggering the spatial positions of CCDs. With the RGB three-CCD method, offsetting R and B against G is virtually the only way available to apply spatial-offset imaging. Fig.2(a) shows the spatial position of three CCDs. The location of R-CCD and B-CCD is shifted by a half-pixel interval from that of G-CCD to obtain a high-resolution luminance signal with mixing ratio described in Fig.2(a).

With the four-CCD system, on the other hand, we can be more flexible. From among a number of possibilities, we have selected a way that shifts G1 and G2 so that G1 corresponds to R and G2 to B, as shown in Fig. 2b. Offset imaging is carried out between R and B as well. This arrangement, i.e. offset imaging within the same G channel, provides two advantages: lessened influence of chromatic aberration and enhanced effects of spatial-offset imaging for all color signals except R and B monochromatic colors. These points are examined later in detail in the chapter IV.

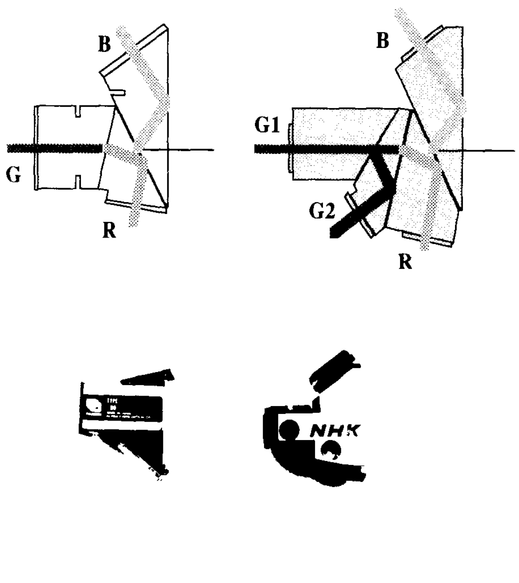


Fig.1 Comparison between
RGB prism (left) and 4CCD prism (right)

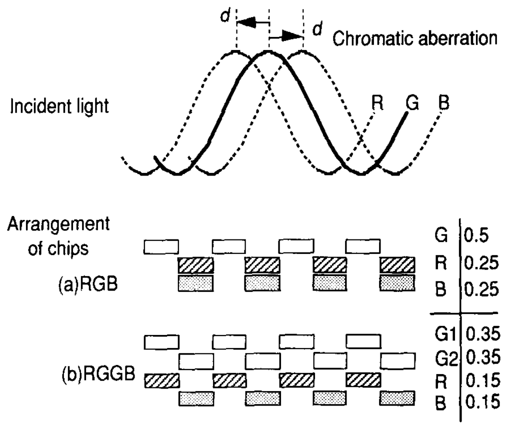


Fig. 2 Spatial pixel offset imaging

III. FEATURES OF FOUR-CCD IMAGING SYSTEMS

We studied the features that may arise from reducing the number of pixels of image-pickup devices and increasing the number of such devices.

-High Resolution

Adequate resolution is secured as two 1.3 million pixel CCDs, i.e. spatial sampling points of 2.6 million, are allocated to the G channel which accounts for 70% of the luminance signals. The resolution of the chromatic signals is also sufficient because 1.3 million pixels are assigned to the R and B channels respectively.

-Good Sensitivity

Generally, as it is difficult to proportionally shrink the pixel separation area, the aperture ratio can be made greater and sensitivity higher if the pixel area is large. The same applies to the on-chip micro-lenses of several micron intervals, which compensate for the decrease in the aperture ratio of the CCD itself.

-High Dynamic range

The greater the pixel area, the wider the dynamic range as the maximum transfer capacity is determined by the area of the photodiode and transfer section. In the four CCD system, two CCDs are allocated to G, which is most likely to get saturated, and the G channel's maximum transfer capacity is therefore twice as much.

-Noise

Random noise, which occurs in the CCD and cannot be removed, worsens by 3 dB in the G channel.

-Highlight characteristics

Greater maximum transfer capacity works better in dealing with blooming. As to smear, a shielding structure can be made more easily if the pixel area is large.

- Good Production ease

Needless to say, the larger the pixel area, the easier it is to produce the CCDs and the higher the yield. This production ease is expected to bring down the price as well.

-Low Electricity consumption

Power consumption increases as there is one more CCD to drive. On the other hand, it decreases thanks to the lower drive frequency.

-Small Size

The camera using four CCDs can be made as small as the one with three CCDs if a new color separation prism for the four-chip CCD camera is realized having the same size as the conventional three-separation prism. (shown in Fig. 1.) Such a prism has to be developed for other reasons, i.e. the optical system has to meet the standards of a 2/3-inch optical system including the length of the optical path in order to maintain the compatibility. Additional electric circuits for an extra CCD only occupy a small portion of the whole system.

These observations show that the four-CCD imaging system poses few problems in terms of power consumption and size, although there is the matter of noise as the band is widened in the G channel. The system will be particularly useful in the dynamic range, an area that gives cameras with simply reduced CCDs a lot of problems.

IV. EFFECTS OF CHROMATIC ABERRATION ON RESOLUTION

The solidification and higher resolution of an image pickup device accentuate the problem of chromatic aberration in the lens. What this means is that the lateral chromatic aberration cannot be absorbed through registration correction (such absorption is possible with the image-pickup tube camera). Further, it has now become necessary to fully utilize the characteristic of the new pickup device, i.e. the same resolution from the center to the periphery of the picture. The target figure is one half or less the scanning line (width) for the whole screen[5], but this goal is not easy to achieve, especially with the smaller optical format.

With regard to the four-CCD and three-CCD methods, we examined the effects on the resolution of lateral chromatic aberration. The image size was 2/3 inch, and the number of pixels was 1.3 million.

As an input signal, we considered a 1-D frequency sweep signal expressed by the following formula.

$$g = Cos\,(\pi f^2) \qquad (1)$$

Chromatic aberration is set at d between G and R and between G and B, as shown in Fig. 2. With f_p expressing the spatial frequency of the cycle, R and B are then expressed by the following.

$$r = Cos\,(\pi f^2 + 2\pi \frac{f}{f_p}) \qquad (2)$$

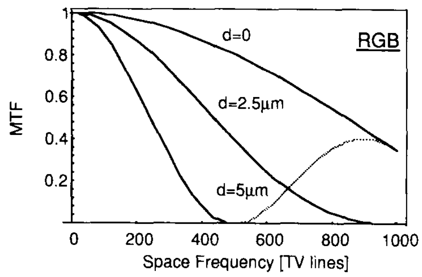
$$b = Cos\,(\pi f^2 - 2\pi \frac{f}{f_p}) \qquad (3)$$

With r, g, b obtained from the above formulas, the luminance signal y is calculated as follows from the ratios described in Fig. 2.

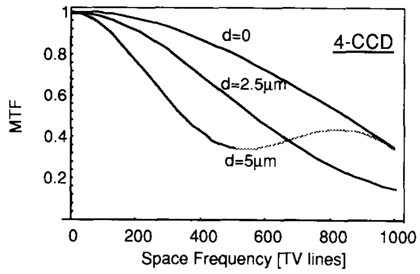
$$\begin{aligned} y &= 0.5\,g + 0.25\,r + 0.25\,b \\ &= 0.5\,Cos\,(\pi f^2) + 0.25\,Cos\,(\pi f^2 + 2\pi \frac{f}{f_p}) + \\ &\quad 0.25\,Cos\,(\pi f^2 - 2\pi \frac{f}{f_p}) \\ &= Cos^2\,(\pi \frac{f}{f_p})\,Cos\,(\pi f^2) \qquad (4) \end{aligned}$$

In this formula, $Cos^2\,(\pi \frac{f}{f_p})$ becomes the envelope of the output signal, expressing the MTF of the luminance signal. In this case, therefore, the luminance signal response is zero at a spatial frequency of $f_p/2$. When d is 2.5μm (about half the scanning line), for instance, MTF is zero with about 1080 TV lines in the RGB method, and the effects of spatial-offset imaging are far from adequate. With the quad CCD imaging system, on the other hand, enough response can be obtained. This is because about 40% of the signals remain through offsetting within the G channel even after subtracting the canceled out portions by R and B.

For the methods shown in Fig. 2, we calculated the MTF of the luminance signal against a white light when the CCD aperture ratio was 50%.



(a) RGB system



(b) RGGB system

Fig.3 Calculated MTF of the luminance signal

The lateral chromatic aberration d was used as a parameter. The results are shown in Fig. 3 . With the RGB method, MTF sharply drops as the aberration increased, particularly when it nears 5μm (about one scanning line) at which point the effectiveness of spatial-offset imaging becomes almost nil. With the four-CCD system, on the other hand, signals from the G channel account for 70%, leaving enough response even after the canceled out portions of the offset signals from the B and R channels are subtracted.

To verify these calculations described, we measured SAR(Signal to Alias Ratio)[6] at 800 TVlines. It is known that the degree of aberration is greater in the peripheral area of the lens than at the center. With this knowledge, we were able to measure how chromatic aberration affects the RGB and four-CCD systems differently. The greater the effects of aberration, the smaller the effects of spatial offset imaging. As a result,

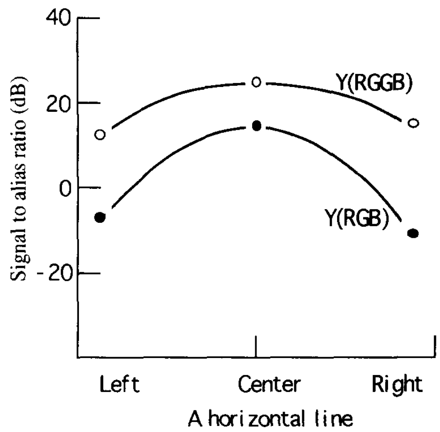


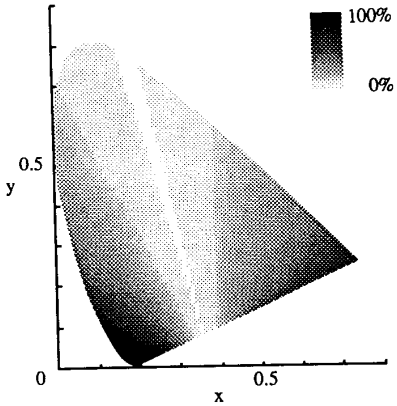
Fig. 4 Signal to alias ratio (dB)
in the liminance signal of a horizontal line

the alias signal portion increases, and SAR is reduced. The result of the measurement are shown in Fig .4. It is clear that SAR is smaller in the peripheral area of the lens than at its center with both RGB and the four-CCD system, apparently as a result of chromatic aberration. It can also be seen from the results that the degree of the drop in SAR is greater with the RGB camera than the four-CCD one.

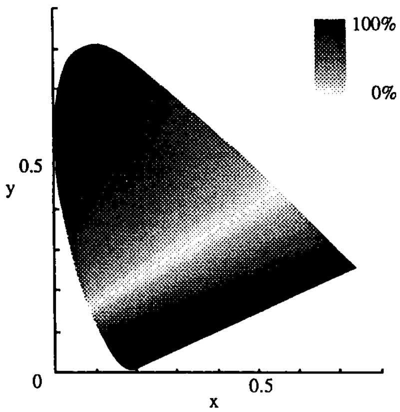
V. COLOR RESPONSES

Spatial-offset imaging by the RGB method is effective for uncolored objects, but not so for R, G or B monochromatic color. This is apparent from the fact that spatial-offset imaging is done between color channels. The problem is not so much the lack of resolution of the monochromatic object as alias disturbance when such an object is captured. With the luminance signal ratios as stated in Fig. 2, alias signals can be completely canceled out in the RGB method if R, G and B signals satisfy the equation $2g = r + b$, where g, r, and b represent each component respectively.

In the four- CCD method, on the other hand, alias signals in the G channel are always canceled out between G1 and G2. Therefore, alias cancella-



(a)RGGB system



(b)RGB system

Fig.5. Calculated alias component

tion is complete if $r = b$ regardless of the G channel. This condition is much easier to achieve than $2g = r + b$ as required of the RGB method. In other words, with the quad CCD system, spatial-offset imaging is effective in suppressing alias disturbance over a wider range of colored signals.

To quantify this point, we calculated the alias level in a *xyz* space with a constant *y*, and illustrated the result on a CIE chromaticity diagram. The procedures are as follows.

First, the alias is calculated on the plane $(x_l,y_l,z_l)\,|y_l = 0.1$ with x_l and z_l being variables. Alias components for RGB and quad CCD are given by the following.

$$A_{RGB} = ABS\,(0.5\,g - 0.25\,r - 0.25\,b) \qquad (5)$$

$$A_{RGGB} = ABS\,(0.15\,r - 0.15\,b) \qquad (6)$$

Where, *ABS* is an absolute value. We used the following conversion matrices between x_l, y_l, z_l and *r*, *g*, *b*...

$$\begin{pmatrix} r \\ g \\ b \end{pmatrix} = \begin{pmatrix} 1.9106 & -0.5326 & -0.2832 \\ -0.9843 & 1.9984 & -0.0283 \\ 0.0534 & -0.1185 & 0.8985 \end{pmatrix} \begin{pmatrix} x_l \\ y_l \\ z_l \end{pmatrix} \Bigg|_{y_l=0.1} \qquad (7)$$

Next, the results are projected from the $y=0.1$ plane onto a plane $(x,y,z)|x+y+z=1$ through the origin.

$$\left. \begin{aligned} x &= \frac{x_l}{x_l+y_l+z_l} \\ y &= \frac{y_l}{x_l+y_l+z_l} \end{aligned} \right|_{y_l=0.1} \qquad (8)$$

Finally, the results are projected parallel onto a $z=0$ plane, and plotted on the CIE chromaticity diagram.

Fig.5(a) and Fig. 5(b) show the plotted alias components for the RGGB and RGB system respectively, graphically indicating the ratios between the signal and the alias of the luminance signal. The area of 0% indicates that there is no alias, meaning that alias is completely suppressed through spatial-offset imaging. The area of 100%, on the other hand, means the occurrence of alias whose level is the same as that of the signal. With the RGB system, alias is effectively suppressed along the straight line of $2\,g = r + b$, but it is very much evident in other places, especially near R, G, B monochromatic colors and the space between R and B. With the quad CCD system, alias is suppressed over a much wider area, particularly the G alias which is completely held down thanks to offset imaging between the two G channels. Alias is also significantly reduced in the signals between R and B as offset imaging is in effect between R and B channels. Alias is rather evident, however, in the portions of R and B monochromatic colors.

VI. PROTOTYPE CAMERA

Fig. 6 shows a block diagram of the prototype. Its structure is basically the same as that of the RGB version, with the difference being that there is a four color separation optical system instead of an RGB one, and an extra CCD drive circuit and head amplifier each. After the two G channels are combined, the signal is processed virtually in the same way as in the RGB system. The prototype uses a 2/3-inch CCD with 1.3 million pixels.[7] It houses a camera head measuring only 11W x 22H x 36D cm, with a built-in vertical DTL circuit using small glass delay lines that consume only small amounts of electricity[8]. This arrangement has opened the way for developing an easy-to-carry version. The camera is capable of very high performance, as shown in Table 1, almost on a par with that of 1-inch HDTV cameras with CCDs each having 2 million pixels.

The number of spatial sampling points differs between G and R/B, and this required special consideration in the design of the optical LPF. For G, we placed an optical LPF with the null point at $4f_n$ in front of the prism in order to secure response up to $2f_n$ (f_n: Nyquist frequency of the CCD) during offset imaging, and held down visible low frequency alias portions. For R and B, the LPF should have its null point at $4f_n$ if the emphasis is on enhancing the offset imaging effects between R and B, but the null point should be at $2f_n$ if the priority is suppressing the alias of monochromatic colors. We chose the one with its null point at $2f_n$, as we wanted to prevent the alias component near the DC area of the chromatic signal from degrading the picture quality. We placed this LPF between the R CCD and the prism and between the B CCD and the prism. The frequency characteristics of the LPFs are shown in Fig. 7.

Measured amplitude response (AR) is plotted in Fig.8. An MTF is calculated from the characteristics of an ideal lens, the optical LPFs and the aperture response of the CCD. The limiting resolution of each single CCD is about 700 TV lines, therefore, the AR characteristics prove that the spatial pixel offset imaging works successfully and improves the resolution dramatically. The value at 800 TV lines is about 40%.

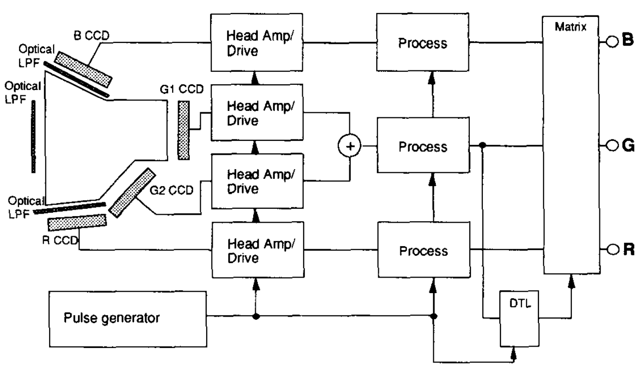


Fig.6 Block diagram of the prototype camera

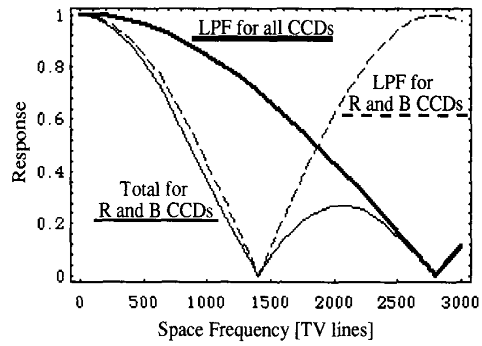


Fig. 7 Characteristics of optical LPFs

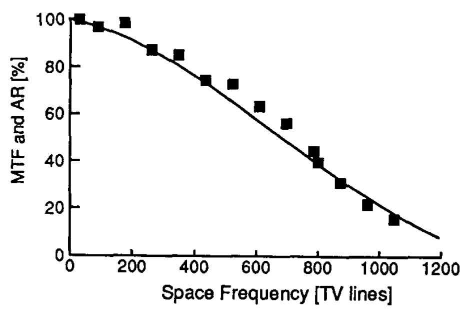


Fig. 8 Measured amplitude response (plotted) and calculated MTF (solid line)

VII. CONCLUSION

We have proposed a four- CCD imaging system and developed its prototype camera. The prototype has demonstrated the validity of the system for the first time that high quality pictures can be produced even with 1.3 million pixel CCDs in the 2/3-inch optical format. The system lessens the negative effects of chromatic aberration by allocating two CCDs to the G channel and one each to the R and B channels. Further, the alias level is held down over a wide range of the chromatic space.

Manufacturers started the production and marketing of HDTV four-CCD cameras in the fall of 1994 in corporation with NHK. The size of the camera head is only 96W x 250H x 293D mm including the 1.5-inch viewfinder and weighs 5.7 Kg; this compactness and lightweight are one of our major development targets. This world-first HDTV four-CCD camera is used primary for news gathering applications. The great Hanshin earthquake provided such an occasion.(shown in Fig.9)

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Table 1 Specifications of the system

Pickup method	4-CCD (GGRB)
Horizontal resolution	1200TV lines
Sensitivity	2000lx F5.0
SNR	52dB

Fig.9 Four-CCD camera being used for news gathering after the great Hanshin earthquake

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